USING BLUE WHALE (*BALAENOPTERA MUSCULUS*) PHOTOGRAPHIC-IDENTIFICATION SIGHTINGS TO ASSESS POTENTIAL VESSEL-WHALE ENCOUNTERS IN THE SANTA BARBARA CHANNEL

by

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Abstract

In 2007 six blue whales (*Balaenoptera musculus*) were found dead in the Southern California Bight with four of the deaths resulting from vessel strikes. To reduce the spatial overlap of vessels and whales, the United States Coast Guard proposed shifting the southern Santa Barbara Channel shipping lane north by one nmi. We used sighting rate predictions from generalized additive models to assess potential vessel-whale encounters in the current and proposed traffic separation schemes. Sightings were collected during coastal-based photo-identification surveys between June - November from 2001 to 2009. In total, 11,037 km of track-line was searched, yielding 602 sightings of 393 uniquely identified blue whales. Whales were strongly associated with spatial covariates and bathymetric features, with the highest sighting rates predicted in close proximity to the shelf edge on steep south facing slopes and shallow northeast facing slopes. The proposed traffic separation scheme could reduce potential vessel-whale encounters by 15%.

Keywords: Balaenoptera musculus; blue whale; generalized additive model; negative binomial; ship strike; vessel

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Blue whale sighting rates

1.1 Introduction

1.1.1 Blue whales

Until the beginning of the twentieth century, blue whales (*Balaenoptera musculus*) were abundant in every ocean except the Arctic. Prior to the invention of the steam engine and deck-mounted harpoon cannons, the speed of the blue whale made it difficult for whalers using sailing-vessels to hunt them on a large scale [1]. Beginning in the 1860's and lasting until the mid-1960's intensive industrial whaling reduced blue whale abundance from around 200,000 to around 16,000 individuals [2]. Despite complete protection in 1966 by the International Whaling Commission (IWC), blue whale numbers continue to remain low [3], with global population estimates in the range of 10,000 - 25,000 individuals [4].

Though whaling is no longer a concern, anthropogenic mortality continues to threaten the recovery of blue whales. In the Gulf of St. Lawrence, at least nine percent of photographed blue whales have injuries or scars attributed to vessels [5]. Recovery plans state that appropriate measures to reduce or eliminate vessel strikes and entanglement in fishing gear are essential to population growth [6, 1]. Additional potential pressures on the population include: natural mortality, anthropogenic noise, competition for prey resources, habitat degradation, and vessel disturbance. Predation by killer whales remains the only known source of natural mortality [7], though the dependence of killer whales on large adult baleen whales as a primary food resource remains debated [8, 9, 10, 11, 12, 13].

1.1.2 Vessel strikes

Collisions between vessels and whales occur world-wide, with reports comprising eleven species: blue, Bryde's (*B. brydei*), fin (*B. physalus*), gray (*Eschrichtius robustus*), humpback (*Megaptera novaeangliae*), killer (*Orcinus orca*), minke (*B. acutorostrata*), North Atlantic right (*Eubalaena glacialis*), sei (*B. borealis*), southern right (*E. australis*), and sperm whales (*Physeter macrocephalus*) [14]. Reports of fatal vessel-whale encounters have steadily increased with increases in the number of commercial vessels in the world fleet and increases in the average speed of commercial vessels [15, 16]. Vessel strikes are an important source of mortality for several species of baleen whales [15], particularly North Atlantic right whales, where vessel strikes accounted for 53% of determined deaths in necropsied individuals between 1970 and December 2006 [17]. The international problem is currently being addressed by the IWC through a Ship Strike Working Group comprised of 16 countries working to quantify vessel strikes, standardize reporting protocols, and develop mitigation procedures [18]. Additionally, to reduce the potential for vessel-whale encounters some coastal states have implemented various vessel routing changes [19, 20, 21, 16] and mandatory [22, 23, 24] or recommended [19, 20] vessel speed restrictions which in some cases were later adopted by the International Maritime Organization (IMO).

1.1.3 Eastern North Pacific blue whales

Knowledge of blue whale distribution, abundance, and migration is often limited by the whales' inaccessibility to research. Nonetheless, of the various blue whale populations only the eastern North Pacific population appears to be recovering strongly [6]. Line transect surveys estimate the current eastern North Pacific population at 1,548 (95% CI: 1,138 - 2,087, CV=0.16) individuals [25], with historical data estimating pre-whaling abundance for the entire North Pacific at 4,900 individuals [26].

Areas of habitat along the California coast are listed as essential to the recovery of eastern North Pacific blue whales [27], but unfortunately the California coast is also home to eleven publicly-owned commercial ports, with three being major United States (US) ports: Los Angeles, Long Beach, and San Francisco Bay. From 1991-1995 the average number of blue whale mortalities in California attributed to vessel strikes was 0.2 per year [28]. These stranding data represent minimum numbers, as strandings and vessel strikes often go unnoticed (because whales sink, float offshore, or strand in remote locations) or unreported [29, 15, 30, 18].

In 2007 six sightings of dead blue whales were made in the Southern California Bight, with at least four of the deaths resulting from vessel strikes [31]. Three of the vessel struck whales were found in or near the Santa Barbara Channel (SBC). Annually, at least 6,500 vessels (43% of all U.S. shipping trade) [32] pass through the SBC headed to and from Los Angeles / Long Beach Harbor, North America's busiest port [33]. The anomalous cluster of mortalities in 2007 exceeded the potential biological removal (3.1 per year) for eastern North Pacific blue whales [34], prompting the National Marine Fisheries Service (NMFS) to declare an unusual mortality event (UME). An UME is defined by the Marine Mammal Protection Act (MMPA) as: "a stranding that is unexpected; involves a significant die-off of any marine mammal population; and demands immediate response" [35]. Investigations of UMEs often have four goals: (1) minimize deaths, (2) determine the cause of the event, (3) determine the effect of the event on the population, and (4) identify the role of environmental processes in the event [36]. Because the shipping lanes overlap the eastern portion of the Channel Islands National Marine Sanctuary (CINMS), NMFS and CINMS are working together with both public and industry input to improve the understanding of the risk of encounters between vessels and large whales in the SBC and to evaluate possible long-term management scenarios.

In November 2011, the United States Coast Guard (USCG), assisted by NMFS and CINMS, proposed two amendments to the SBC Traffic Separation Scheme (TSS) to mitigate vessel-whale encounters: (1) shifting the southbound lane north one nautical mile (nmi) and (2) reducing the separation zone from two nmi to one nmi, narrowing the overall width [37]. By shifting vessels away from areas of known blue whale seasonal feeding grounds, ocean-resource managers believe the likelihood of vessel strikes with blue whales will be reduced. The primary purpose of a TSS is to reduce the risk of marine casualties by providing safe routes for vessels proceeding to and from ports. With safety being the primary concern, changes to vessel routes in the SBC are limited by the close proximity of offshore oil rigs along the California Coast, the Point Mugu Naval Training Range (the Department of Defenses largest and most extensively instrumented marine testing zone) located south of the Channel Islands, and other navigational hazards located within the SBC. Additionally, increasing distances traveled or changing speeds of travel will likely affect vessels' voyage costs and could lead to increased emissions further limiting feasible amendments to the TSS.

1.1.4 Vessel-whale encounters

Previous attempts to determine the best location for a TSS in the SBC relied on models using spatially referenced whale sightings collected during standard line-transect surveys which were designed to predict marine mammal encounter rates for the entire US West Coast [38]. Though the generalized additive models (GAMs) built to predict large-scale patterns for the southern California Bight perform as well as models built for the entire US West Coast, the models are not appropriate for modeling the fine scales (under 50 miles) necessary to explore shifts to the TSS within the SBC and fail to capture meso-scale heterogeneity in prey patches [39]. Conceptually it is straightforward to design a survey specific to the Southern California Bight or even the SBC itself, but chartering a vessel to conduct such a survey can be costly and is logistically challenging [40, 41, 42, 43].

When surveys are prohibitively expensive or information is time-sensitive, many researchers attempt to gain information from so-called ”platforms of opportunity.” Platforms of opportunity (POPs) are vessels dedicated to another purpose from which sightings, and sometimes effort, can be recorded (e.g. ferries [44], whale-watching vessels [42, 45], fishing vessels [46], cruise ships [41], commercial whalers [47, 48, 29], and others [49, 50]). Data from such POPs can result in large databases of opportunistic sightings, but present some fundamental problems to the researcher, including non-standardized sampling effort, short duration of field seasons, variability in the quality and reliability of observations, and limits to sampling techniques due to the nature of the vessel and its primary function. Most of these limitations can be overcome when observers are trained and adhere to rigorous protocols and when data collection is broad enough to spatially and temporally cover a range of habitat variability [40]. Using sightings already collected for other purposes is an attractive option for scientists wanting to study important areas that are otherwise prohibitively expensive to survey [51, 41].

Since the mid 1980’s, researchers have conducted photographic-identification (photo-id) studies of blue whales along the US West Coast using small boat surveys [52, 53]. Logistical constraints of the surveys often keep them within near-reach of populated areas and hence where conservation management needs are particularly vital. During most years these vessels provide reasonable coverage of the SBC, as well as known blue whale hot spots. The main aim of the surveys’ is to maximize the number of uniquely identified individual whales which could lead to larger sample sizes compared to traditional POP, where the main aim may be unrelated to cetacean population assessment research. Sightings originating from the photo-id surveys provide us with an opportunity to predict patterns of blue whale habitat-use at fine spatial scales within the SBC.

1.1.5 Research goals

Although spatial overlap of whales and vessels is not equivalent to the risk of a collision, it is a prerequisite, and minimizing spatial overlap between whales and vessels is an effective way to reduce the likelihood of vessel strikes [54]. The objectives of our study were to predict locations in the SBC where blue whales are most likely to occur and quantitatively address the problem of vessel strikes by comparing the predicted sighting rates of blue whales with the current shipping lane configuration and with the lane configuration proposed by the USCG. Because areas in close proximity to the 200 m depth contour should be positively correlated with blue whale sighting rates [39], moving the shipping lanes further from this contour, as proposed by the USCG, should decrease the overall sighting rate within the shipping lanes. Ocean-resource managers in Canada and the US are using a similar spatial analysis approach, comparing the distribution of whales to that of vessel traffic to reduce the risk of ship strikes to the critically endangered northern right whale in the shipping lanes servicing Boston, Massachusetts and the Bay of Fundy [21, 16]. We built non-linear statistical relationships with GAMs to relate photo-id sightings to a range of topographic variables and predict blue whale sighting rates in the SBC.

1.2 Materials and methods

1.2.1 Study area

The SBC, located on the southern coast of California (34.25°N, 120.10°W) (Figure 1.1), is the longest section of east-west trending coastline (130 km long) on the US West Coast. The SBC is further distinguished by the presence of the Santa Barbara Basin, a basin with gentle side slopes to the north and a maximum depth of 589 m on the south side of the basin [55]. Productivity in the region is driven by summertime equatorward winds, known as the California Current System, bringing upwelled cold, salty, and nutrient-rich water from depth to the surface [56].

1.2.2 Sighting and effort data

Data on blue whale occurrence were obtained during 80 coastal-based photo-id surveys between 2001 and 2009 using small (5.3 m) rigid-hull inflatable boats (Table 1.1). Surveys were conducted out of Santa Barbara Harbor, Ventura Harbor, and Gaviota State Park, California, US, during the months of June to November. Survey dates followed southern California trends in peak blue whale abundance [57, 58]. Surveys concentrated on covering the largest possible area and spent more time searching areas where whales were frequently encountered. Additionally, following the 2007 UME, effort was dedicated to searching for whales within the shipping lanes. Global Positioning System (GPS) devices automatically recorded the position (± 50 m), course, and speed of the research vessel at a minimum of every 5 minutes. During surveys, when cetaceans were encountered, the group was followed in attempt to obtain photographs for identification and the position of the terminal dive was recorded. Photographs were taken with 35-mm and digital single-lens reflex cameras equipped with telephoto lenses. If possible, photographs of natural pigmentation patterns were taken of both the right and the left sides and, when shown, the ventral surface of the flukes.

The best photographs from each sighting were selected and compared to a catalog consisting of 2,142 unique blue whales identified since 1986. All photographs were compared by at least two researchers, with all matches verified by a third person (for more details on photo-id methods see Calambokidis *et al.* 2004 [53]). To avoid biases originating from individuals observed more than once a day, only the first sighting of each individual in a day was used in the analysis. Multiple sightings on separate days were treated as independent. All resulting models assume that identified whales behave the same as non-identified whales.

We divided the study area into a grid of 1 km by 1 km cells (totaling 8632 cells) and assigned segments of the survey tracks (track-lines) and cetacean sightings to each cell. All positional data, recorded in latitude and longitude, were plotted on a map with a Lambert Cylindrical Equal Area projection, using the ‘raster’ package [59] in the statistical software R (version 2.14.1; [60]). Maps projected on equal area grids are preferred for spatial analysis because latitude and longitude do not reflect consistent distance measures. Track-lines were interpolated as straight line paths between GPS locations. In the event of a loss of satellite connection, or some other reason for GPS failure, track-lines were truncated to portions containing position updates within 5 minutes of each other and only sightings with associated track-line segments were included in the analysis. The length of track-line within a cell was significantly correlated with the number of trips through the cell ($r = 0.922$, 95% $CI : 0.917 - 0.927$, $p < 0.005$) and was therefore considered to be a good representation of search effort (Figure 1.2). Independent sightings of photo-id whales were summed in each cell as the response variable.

Data from all years and months were combined, and any seasonal or annual variations in sighting rate or habitat utilization were not investigated because the main aim of the study was to investigate habitat utilization in relation to seabed topography. Additionally, single surveys or single years were not used independently because of the limited number of sightings and limited coverage of habitat variability within the smaller sample unit.

1.2.3 Topographic data

We used six continuous predictor variables: depth, slope, aspect, distance to the 200 m depth contour, latitude, and longitude. Topographic variables were included as proxies for prey abundance or availability, which are expected to directly influence cetacean distributions [40]. Significant relationships between topographic variables and cetacean population distributions have been observed for many species, including bottlenose dolphin (*Tursiops truncatus*) in the northwest Atlantic [61] and harbor porpoises (*Phocoena phocoena*) in northern California [62]. Specific to blue whales, topographic variables are often selected as predictors in models describing blue whale presence [63, 29, 38]. Slope was included to provide a measure of bottom topography because topography is known to influence upwelling which can play a role in biological productivity and prey availability [64]. Aspect describes the orientation of the seabed and was included to reflect local and regional current flows which affect food supplies [65]. Distance to the 200 m depth contour (contDist) was included to capture the affinity of prey to form dense aggregations near the continental shelf break [66]. Using contDist has an advantage over distance to the coastline by taking depth into account, and thus allowing comparisons between cetacean distributions in regions with different continental shelf extents. Latitude and longitude were included in the model as a proxy for unmeasured variables or to evaluate if the observed sighting rate patterns were being driven by spatial correlation [67].

Bathymetric data originated from a three arc-second resolution digital elevation model (DEM) produced by NOAA's National Geophysical Data Center [68]. Using data from the DEM and the functions in the 'raster' package, each grid cell was assigned values for the four topographic variables. Depth was determined as the average depth in the grid cell, measured in kilometers. Slope and aspect, measured in degrees, were computed with the terrain function using 8 neighbors. The ‘queen’s case’ method uses unequal weighting coefficients for the nearer elevation values that are proportional to the reciprocal of the square of the distance from the kernel center [69]. Distance to the 200 m depth contour was measured as the shortest distance (km) from the center of the grid cell, with distances in waters shallower than 200 m multiplied by negative one. Pair-plots and variance inflation factors (VIF) were used to identify correlated variables. To avoid multicollinearity and model performance issues, the variable with the highest VIF was dropped from further analyses when two variables were highly correlated ($r > 0.75$) [70].

1.2.4 Data analysis

We used generalized additive models (GAMs) to examine the role of topographic variables in predicting blue whales sighting rates in the SBC. Generalized additive models are nonparametric extensions of generalized linear models (GLMs) [71], where the additive predictor may include nonparametric smooth functions of the predictor variables, allowing GAMs to be considerably more flexible than GLMs [40]. The goal was, therefore, to investigate how each variable relates, possibly nonlinearly, to blue whale sighting rates.

The response variable (sum of all independent blue whale sightings in a grid cell from 2001-2009, $E[n_i]$) was assumed to follow a negative binomial distribution, with a log-link function. The general model structure was

$$log(E[n_i]) = \sum_k s_k(z_{ik}) + \text{ offset}(log[\text{trackLength}]_i) \tag{1.1}$$

where s_k are smooth functions of the explanatory variables, and z_{ik} is the value of the kth explanatory variable in the ith grid cell. The sum of the lengths of all the track-line segments (m) within the grid cell was used as an offset to account for unequal sampling effort within the study area. Because equality of mean and variance is rarely found in natural resource data, the negative binomial distribution was thought to be more realistic than the Poisson distribution [72]. Using a negative binomial distribution allowed the variance to adjust independently of the mean.

The models were fitted using the ‘mgcv’ package ([73]) within R (version 2.14.1; [?]). Covariates were fitted as smooth functions, using thin plate regression splines (TPRS), the default smoothing spline. Thin plate regression splines allow the estimation of smooth functions without specifying knot locations, a potentially subjective step required by other smoothing methods [67]. Smoothing splines were fitted using multiple generalized cross validation (mgcv) procedures, where the ‘mgcv’ package automates a training and cross-validation approach as part of model fitting. The amount of flexibility given to a smoothing spline is determined in a maximum likelihood framework by minimizing the generalized cross validation (GCV) scores of the whole model [74]. For single covariate smooth functions the default *dimension* in ‘mgcv’ is 10, which is equivalent to setting the maximum number of degrees of freedom for the smooth function at 10. One-dimensional smooth terms were permitted in the model as curves or as linear terms. Latitude and longitude and slope and aspect were presented in two-dimensional surfaces to allow for flexible surfaces. *A priori*, a scale invariant tensor product smooth (te) was chosen for slope and aspect in place of an isotropic smooth (s), because a one unit change in aspect is not assumed to be the same as a one unit change in slope. Tensor product smooths result in a penalty for each marginal basis of lower dimension. For all model fitting, the dispersion parameter (θ) was initially set to one, allowing the package to perform smoothing parameter selection using unbiased risk estimation (UBRE), prior to using Akaike information criterion (AIC) to search for the optimal value of θ. A full fit of the model is required, prior to searching over the supplied range of values for θ, which makes the fitting process slow. For all models, a range of 0.01 to 5 was used to search for the optimal value of θ. To reduce potential overfitting of smooth functions the estimated degrees of freedom in a smooth function were forced to count for 1.4 degrees of freedom in the UBRE score ([67]), thus penalizing the GAM function for using too many degrees of freedom as suggested by Kim and Gu [75].

We used AIC to determine the ‘best’ model from a set of *a priori* selected candidate models [76]. We also calculated the percentage of deviance explained as a measure of absolute model fit for the final model. The fit of the ‘best’ model was visually assessed by plotting the relationship between the observed and fitted values to look for patterns in the residuals and identify unexpected patterns in the deviance. We used quantile-quantile plots and histograms to examine the distribution of the model residuals and check whether the assumption about the distribution of errors holds.

1.2.5 Predicting sighting rates

Maps of predicted sighting rates were produced to visually verify whether or not predicted areas of high whale sightings matched observed effort corrected sightings. Predictions were made on a 1 km × 1 km grid, the same scale used to create the GAM. Sighting rates were predicted for each grid cell with the *predict.gam* function in 'mgcv' and plotted in R for visualization. Standard errors of predictions were based on the Bayesian posterior distribution of the model coefficients, and part of the output generated by the *predict.gam* function.

We assume the probability of a vessel-whale encounter is proportional to the number of whales in the TSS, using sighting rates as a proxy for the likelihood of a ship and whale coming into contact. It is assumed that the presence of ships in the channel is constant across both the inbound and outbound lanes, as few ships deviate from the TSS within the confines of the study area. The relative probability of a vessel-whale encounter was calculated as the sum of the predicted relative sighting rates within the inbound and outbound lanes in the current TSS and the TSS proposed by the USCG. Results are summarized as the percentage change in relative probability for each TSS option relative to the status quo of the current TSS:

$$\%\Delta = \frac{(\text{relative prob. proposed southbound TSS} - \text{relative prob. current southbound TSS})}{\text{relative prob. current southbound TSS}} \tag{1.2}$$

1.3 Results

1.3.1 Surveys

Blue whales were observed in seven of nine years and were most commonly sighted near the shelf edge, north and west of the Channel Islands. Data were collected during 80 trips between November 11, 2001 and September 22, 2009 with the largest number of trips occurring in 2002 (Table 1.1, Figure 1.3). Forty-five percent of the study area had associated effort data (3,844 of 8,632 cells) and 6% of the cells with effort (220 of 3,844 cells) had at least one independent blue whale sighting. In total, 602 sightings of 393 uniquely identified blue whales were included in the models. Blue whales were most frequently encountered in close proximity to the 200 m contour and on south facing slopes (Table 1.2). The mean water depth where blue whales were sighted was 0.296 km with a maximum depth of 1.025 km

(Table 1.2; standard deviations (SD) for all environmental variables and summary statistics for the entire study area are also presented in Table 1.2). Depth and distance to the 200 m contour were strongly correlated (0.825, 95% $CI: 0.815 - 0.835$, $p < 0.005$), with depth increasing as the distance from the 200 m depth contour increased. Depth was not included in the analysis as depth had a higher VIF (3.5) than contDist (3.4), indicating depth was correlated with other variables as well. Once depth was removed from the analysis, VIFs and correlation coefficients for the remaining five variables were all lower than 3 and 0.75 respectively, indicating no further variables needed to be removed from the analysis.

1.3.2 Generalized additive models

The best-fitting model predicting blue whale sighting rates, determined by AIC, includes slope, aspect, contDist, latitude, and longitude, and has the following form: sightings ˜ te(slope,aspect) + s(contDist) + s(latitude,longitude) (Table 1.3). Based on delta AIC values there is some uncertainty whether to use a tensor product smooth or an isotropic smooth for the spatial covariates, latitude and longitude. With a delta AIC of less than two, there is relatively similar support for both models, but the choice of smooth did not affect the overall patterns and therefore only the 'best' model will be explored (Figures A.1). The selection process resulted in a final model with an adjusted R-square of 0.56 and 53.9% of explained deviance. All smooth functions for the 'best' model indicate nonlinear relationships are appropriate (Figures 1.4, 1.5, 1.6). According to the model response curves, interactions between slope and aspect and latitude and longitude are appropriate, as the slopes are not independent of each other. All model assumptions were met and diagnostic plots did not indicate any concerning patterns (Figures A.2, A.3, A.4). The dispersion parameter (k) was estimated at 0.757.

Sighting rates of blue whales appear to be strongly associated with topography. Sighting rates were highest on steep southern slopes and shallow north-eastern slopes (Figure 1.6). There was strong evidence for the effect of distance to the 200 m contour, with increased sightings in waters near the contour edge and deeper. Preferences for waters greater than 15 km from the contour edge has considerable uncertainty associated with it (see 95% confidence limits) due to the lack of sample size at large (>12 km) distances from the contour (Figure 1.4). The smooth function for latitude and longitude, which represents the variation of the fitted response surface holding all other predictors fixed at the mean, showed a reduced preference for the northwest, southeast, and southwest corners of the study area, with the northwest corner predicting the lowest sighting rates (Figure 1.5). The highest fitted values occur at 34.1°N and 120.6°W, the area to the west of San Miguel Island.

1.3.3 Predictions

Visual inspection of predictions from the 'best' model (Figure 1.7) compare favorably with the overall sighting rate patterns observed during the surveys (Figure 1.8). All observed areas of high concentrations, after adjusting for effort, were identifiable in the predictions. In general, model predictions tend to over-estimate zeros and under-estimate large counts.

1.3.4 Shipping lane configuration

The highest sighting rates are predicted west of San Miguel Island and in the southbound shipping lane north of Santa Cruz Island. The current lane configuration intersects two blue whale hot-spots. While shifting the lanes north by one nautical mile reduces the co-occurrence of the shipping lanes with the hot-spot closest to Santa Cruz island, it would center the lanes on the hot-spot near Anacapa island. Estimates of sighting rates summed in the southbound TSS proposed by the USCG are lower (1.863^{-05}) than the current southbound TSS (2.198^{-05}) by 15% (Figure 1.9).

1.4 Discussion

1.4.1 Generalized additive models

Generalized additive modeling is becoming a useful and standard tool for examining the relationship between cetaceans and their environment, with the great benefit of capturing non-linear relationships through a data-driven approach [40]. The model presented here is the first to predict blue whale sighting rates specific to the SBC. The model is consistent with what is known about blue whales and their tendency to feed in waters of close proximity to the California shelf edge during the months of June through November [52, 77]. More specifically, the non-linear relationships were consistent with patterns from models predicting blue whale density for the entire California coast, with the highest encounter rates associated with the shelf edge and areas of high slope [38].

Though it is beyond the capability of our model to predict sighting rates in deep waters far from the self-edge ($> 12 - 20$ km), the smooth for contDist predicts higher sighting rates in deep waters far from the shelf-edge than in shallower waters in close proximity to the shelf edge. It is not uncommon for blue whales to be sighted in low densities up to $200 - 300$ km offshore during the summer months [78], but it is unclear whether high predicted sighting rates at distances of $12 - 20$ km from the shelf edge presented here are animals foraging or transiting in or out of the SBC. Oceanographic conditions could be causing similar conditions at the shelf edge and offshore areas where eddies are common, causing contDist to be a proxy for oceanographic dynamics leading the model to predict higher sighting rates at both locations. More dedicated effort is needed in waters far from the 200 m depth contour to elicit a more definitive pattern.

The majority of cetacean-habitat relationships are determined by cetacean responses as predators, with prey availability being the limiting factor [40]. Migrating blue whales come to California primarily to feed on dense subsurface seasonal aggregations of two euphasiids species: *Euphasia pacifica* and *Thysanoessa spinfera* [79, 57]. Consequently, large concentrations of whales correlate with peak euphasiid densities predictably located near topographic breaks downstream of coastal upwelling centers [57, 79, 66]. Topographic breaks are thought to provide euphasiids with the ability to undergo vertical diel migrations in excess of 100 m while remaining in highly productive waters [79], which explains why the contDist smooth predicted reduced sighting rates in waters shallower than the 200 m contour. At the east end of the SBC the TSS proposed by the USCG runs parallel to the shelf edge and could lead to more whales coming into contact with vessels because of their affinity for waters deeper than the shelf edge rather than shallower. In this area, the current lanes cross the shelf edge at a shallower depth where whales are less likely to be seen.

For the models used in this study to predict sighting rates, the most important assumptions are: (a) unobserved whales behave the same as observed whales; (b) no preference heterogeneity exists among individuals; (c) multiple sightings of the same individual across days had only minimal effect on results; (d) animals' selection of habitat is independent of selections made by all other animals (e) indirect variables that influence habitat preference are correctly identified; (f) effort per grid cell is correctly calculated; and (g) spatial coverage of available habitats is sufficient.

We have no reason to believe assumption (a) is untrue, but this is difficult to test because we do not know how unobserved whales behave. Because the model includes late season (October and November) sightings (15 of 602 sightings) when males are known to spend more time at depth singing for mating purposes [80] and are less likely to be photographed, the model results could be positively biased towards female sighting rates. The sample size was too small to create individual models for both peak foraging times and late season mating behavior, though when the late season sightings were removed from the analysis the relationships between sightings and covariates did not change (Figure A.5). Individuals appear to use the available habitat equally, and by combining data from multiple years biases surrounding assumption (b) were minimized. As long as assumption (b) holds true, assumption (c) should have no affect on the model results.

In general blue whales are not gregarious or territorial, yet assumption (d) may be violated when animals are traveling in pairs, where the paired association is social in nature and includes a male and female. Surveys took place during the feeding season rather than breeding season, which should minimize spatial autocorrelation of sightings for reasons unrelated to habitat preference. Although the lack of sighting independence may have affected the relative strength of modeled relationships, it is unlikely to have impacted the results to an extent that invalidates our general conclusions [29].

Assumption (e) is hard to meet for any species, particularly for species that spend the majority of their life under water. Few cetaceans are studied in enough detail to develop specific hypotheses regarding the ecological processes determining their distribution and researchers are often limited by the data available and rely on physical features of the study area as covariates [40]. Indirect gradients, such as slope, aspect, and depth, have no direct physiological relevance for a species ability to gather matter and energy but they often provide good correlation with observed species patterns, replacing the need for measuring direct gradients [81]. Indirect gradients frequently replace a combination of direct gradients, where the combination may be specific to the study area, making results inapplicable to new geographical extents because the same indirect gradients could have different affects on whales or their prey in new locations. Clearly there may be other dynamic variables with the potential to explain blue whale sighting rates: sea surface temperature (SST), sea surface chlorophyll, mixed layer depth, and salinity [25, 63]. In our analysis we did not consider time-varying covariates because the SBC TSS is currently designated with fixed boundaries and no time variation, making interannual and seasonal variation irrelevant to model predictions. Additionally, due to the small number of sightings we choose to include static topographic variables that were available for the entire study period. Nevertheless, our models explained 53.9% of the deviance and even incomplete descriptions are valuable when attempting to minimize adverse anthropogenic impacts on cetaceans [82].

Although surveys were non-regular and searches were in a non-uniform pattern, every attempt was made to ensure assumption (f) was met, leading to an unbiased sighting rate. Because surveys were aimed at maximizing whale encounters rather than ensuring habitats were sampled equally or randomly, using the length of track-line in each grid cell as an offset enabled us to account for increased sightings in areas that were searched frequently. Using the length of track-line per grid cell did not account for situations when photo-id researchers received radio communication from aerial surveys of whale presence in the SBC. The east end of the SBC was rarely searched by photo-id surveys unless researchers were informed whales were currently in the area, leading to a sighting rate in the eastern end of the channel that may be positively biased.

With respect to assumption (g), the only variable that was not covered across its range within the SBC was contDist. Surveys did not spend as much time searching for whales in deeper offshore waters, partially due to logistical constraints but also due to prior knowledge that whales do not frequent areas far from the 200 m contour. An artificial relationship between whales and contDist is unlikely because areas of non-shelf habitat must be crossed while transiting to the shelf. Although survey vessels often transit at higher speeds while in areas with low historic whale sightings, observers are always on effort thereby increasing the spatial coverage of contDist and reducing the potential bias.

Our model indicates that blue whales are strongly associated with latitude and longitude which are proxies for biological or physical properties that ultimately affect cetacean distributions. For ocean-resource managers wanting to propose potential TSS configurations it would be nice to know for what these spatial covariates are proxies. Few marine mammal species have been studied in enough detail allowing covariates to be chosen based on an *a priori* understanding of the factors influencing a species distribution. Although the current TSS is both temporally and spatially stationary, adding average or maximum SST or the number of days above a threshold SST to the model could capture the affinity of blue whales to associate with thermal fronts that lead to enhanced phytoplankton, zooplankton, and fish biomass [64]. Because euphasiids are less capable of active horizontal movements than fish species, blue whales, which feed almost exclusively on krill, are thought to be more influenced by thermal fronts than other baleen whales [83]. Even if data for oceanographic condition data were available on the proper scale and added to the model, it is unlikely that all of the variability accounted for by the spatial covariates would be removed and therefor cause AIC to favor a model without latitude and longitude.

Spatial distribution patterns captured by the model presented in this study demonstrate how useful ecological inferences can be made from data collected in a non-systematic manner. Models developed from systematic line transect surveys predicted heterogeneity within the SBC [39], but failed to accurately predict patterns specific to the SBC, such as high densities north of Santa Cruz Island. Predictions generated from this study using photo-id surveys, adequately predicted areas of high density within its respective study area. Models developed for this study are capturing blue whale micro behavior, whereas models developed for the entire US West Coast are modeling blue whale habitat preferences at the macro scale. Additionally, models from photo-id studies revealed blue whale preferences for shallow southeast facing slopes as well as showing preference for the known relationship between blue whales and areas of steep slope. Although aspect is rarely included in cetacean-habitat studies, aspect was the most important variable in determining Blainville's beaked whale (*Mesoplodon densirostris*) habitat utilization in the Bahamas [84]. The exact reasons for the link between aspect and blue whales, or Blainville's beaked whales, remains unclear, however, it may be related to interactions between topography and local currents and how they affect prey availability and/or growth.

1.4.2 Vessel-whale encounters

This study presents an objective and quantitative framework for predicting blue whale sighting rates as the basis for an assessment of potential vessel-whale encounters in the SBC. Specifically, sighting rates predicted on a spatial grid describe the variation and uncertainty in blue whale occurrence over space, facilitating visual inspection of potential vessel-whale encounters under various TSSs.

Mechanistic processes describing cetacean distributions may never be fully understood and consequently cetacean-habitat models do not perfectly predict cetacean distributions yet few studies provide metrics regarding the uncertainty in model predictions [40]. When uncertainties were taken into account in the southeastern US regarding potential vessel-whale encounters with North Atlantic right whales, results failed to differentiate between the top three scenarios [85]. The results of our study suggest that shifting the southbound TSS northward has the ability to reduce the number of potential encounters between vessels and blue whales by 15%. To help ocean-resource managers decide on the best way to mitigate vessel-whale encounters in the SBC, results from this study will be integrated into a decision analysis framework providing information regarding the uncertainty surrounding the point estimate of a 15% reduction in potential vessel-whale encounters. Fonnesbeck *et al.* [85] recommends using a Bayesian approach to differentiate between optimal TSSs. A spatial hierarchical Bayesian risk model has the capacity to model uncertainty in model parameters and integrate this uncertainty into risk estimates. As new data are collected the model can be updated, potentially further reducing uncertainty.

Including spatial information on vessel movements in the risk analysis could also lead to more robust estimates vessel-whale encounter probabilities. According to automatic information system (AIS) data used by ships to report their identification, position, course and speed, some vessels choose to enter the southbound TSS south of the true eastern entrance [86]. Sighting rate predictions were highest west of San Miguel Island and depending on how many vessels choose to use the true entrance to the TSS, enforcing the use of the IMO approved lanes may have more of an impact than shifting the TSS itself.

Sighting data reveals where whales are located at the surface but provides little to no information on how whales behave just below the surface where they are still susceptible to vessel strikes, making measurements of potential vessel-whale encounters relative rather than absolute. The availability bias becomes a concern if we believe the bias varies over space, time or environmental conditions [85, 87]. Sightings only characterize habitat use during daylight hours and data from suction cup tags reveal the availability bias varies over time because blue whales can spend up to 70% more time at the surface during nighttime hours and may use the habitat differently, as feeding stops after sunset. More research specific to the SBC is needed to determine if the availability bias varies spatially. How whales move during different times of the day is of concern because shipping traffic in the center of the channel peaks at both daylight and nighttime hours depending on the shipping lane [86].

The effect of reducing vessel speeds, a method thought to reduce the probability of a lethal injury if an encounter should occur [21], is not being investigated here. Speed restrictions and vessel re-routing options are being proposed and enforced in other areas of the North America, in particular in TSSs inhabited by the critically endangered northern right whale [21]. The full implications of reducing vessel speeds on vessel-whale encounters is not completely known, and in 2009 a vessel traveling 5.5 knots struck and killed a blue whale near Fort Bragg, California. There is evidence whales may even surface when exposed to sound stimuli and remain there for an abnormally long time [88, 89], further exposing them to the risk of vessel strikes. Additional research studying the combined effects of speed restrictions and vessel re-routing measures are needed to determine the best mitigation strategy. Furthermore, vessel speed restrictions may place undue safety concerns on vessel mariners by limiting vessel navigation abilities and increased costs to the shipping industry by causing vessels to spend more time at sea.

The consideration of potential vessel-blue whale encounters needs to be balanced against potential vessel-whale encounters with other species in the area whose distribution may differ from that of blue whales and whose conservation status may be more critical. In California, gray whales are the most common baleen whale hit by ships, followed by fin, blue, humpback, and one sperm whale [90]. Traffic separation schemes that shift transit through the Point Mugu Naval Training Range may reduce the risk to blue whales while increasing the risk to fin whales [39]. Furthermore, potential biological removal estimates for each whale species inhabiting the SBC are species-specific and may fluctuate over time. Should additional species specific sighting rates for the SBC become available, weighting them with respect to potential biological removal estimates for each species could provide a framework to rank the importance of shifting the TSS for one species over another. An additional task for future research is to estimate the annual number of potential vessel-whale encounters, as results from this analysis can predict where vessel strikes are most likely to occur, but it cannot predict how many will occur.

1.4.3 Conclusions

The main goals of the present study were to determine if useful blue whale habitat relationships can be generated from photo-id data and to compare relative sighting rate predictions between two TSS configurations. Models predicted blue whale hot spots that were known to exist and revealed blue whale preference for varying slopes depending on the aspect of the seafloor. Model predictions suggest shifting the SBC TSS as suggested by the USCG could reduce potential vessel-whale encounters by 15%. Furthermore, insight into potential vessel-whale encounters outside of the lanes to the west of San Miguel Island will be useful to ocean-resource managers looking to minimize vessel-whale encounters. The framework outlined here is an appropriate way to gain useful information from platforms of opportunity that record sightings and effort. With the increase in boat-based whale watching and other marine tourism, such methods will yield valuable information to scientists and conservation managers alike without increasing vessel traffic or violating whale watching codes of conduct.

1.5 Tables

	Year	Num Trips	ID Sightings	Non Dup ID	Bm Sightings	Est. Total Bm
1	2001	1				
2	2002	20	181	116	228	317
3	2003	4	31	23	42	55
4	2004	8	122	85	114	222
5	2005	9	88	35	82	121
6	2006	1				
7	2007	8	283	187	184	415
8	2008	14	51	35	33	57
9	2009	15	164	121	149	273
10	Sum	80	920	602	832	1460

Table 1.1: Summary of photographic-identification surveys in the Santa Barbara Channel.

	Min SA	Min Bm	Mean SA	Mean Bm	Max SA	Max Bm	SD SA	SD Bm
depth	0.000	0.077	0.318	0.296	1.940	1.025	0.316	0.144
slope	0.000	0.001	0.035	0.073	0.328	0.169	0.042	0.052
aspect	0.000	0.003	3.251	3.219	6.283	6.281	1.625	2.530
contDist	-20.159	-3.455	0.971	1.305	24.897	12.174	7.009	2.556

Table 1.2: Summary statistics of environmental variables for the Santa Barbara Channel study area (SA) and the grid cells containing independent blue whale sightings (Bm).

Formula	df	AIC	delAIC
bmIdND ˜ te(slope, aspect) + s(contDist) + s(Lon, Lat)	46.9	1710.6	0.0
bmIdND ˜ te(slope, aspect) + s(Lon, Lat) + contDist	37.4	1731.7	21.0
bmIdND ˜ te(slope, aspect) + s(Lon, Lat)	36.7	1738.6	28.0
bmIdND ˜ te(slope, aspect) + s(contDist)	23.7	1904.4	193.8
bmIdND ˜ s(contDist) + s(Lon, Lat)	35.6	1730.8	20.2
bmIdND ˜ te(slope, aspect) + s(contDist) + te(Lon, Lat)	40.8	1712.3	1.6

Table 1.3: From the candidate set of models, the model with the lowest Akaike information criteria (AIC) value contained slope, aspect, contDist, latitude, and longitude and was labeled the ‘best’ model. Based on delta AIC values there is some uncertainty whether to use a tensor product smooth or an isotropic smooth for the spatial covariates, latitude and longitude. With a delta AIC of less than two, there is relatively similar support for both models, but the choice of smooth did not affect the overall patterns and therefore only the ‘best’ model will be explored.

1.6 Figures

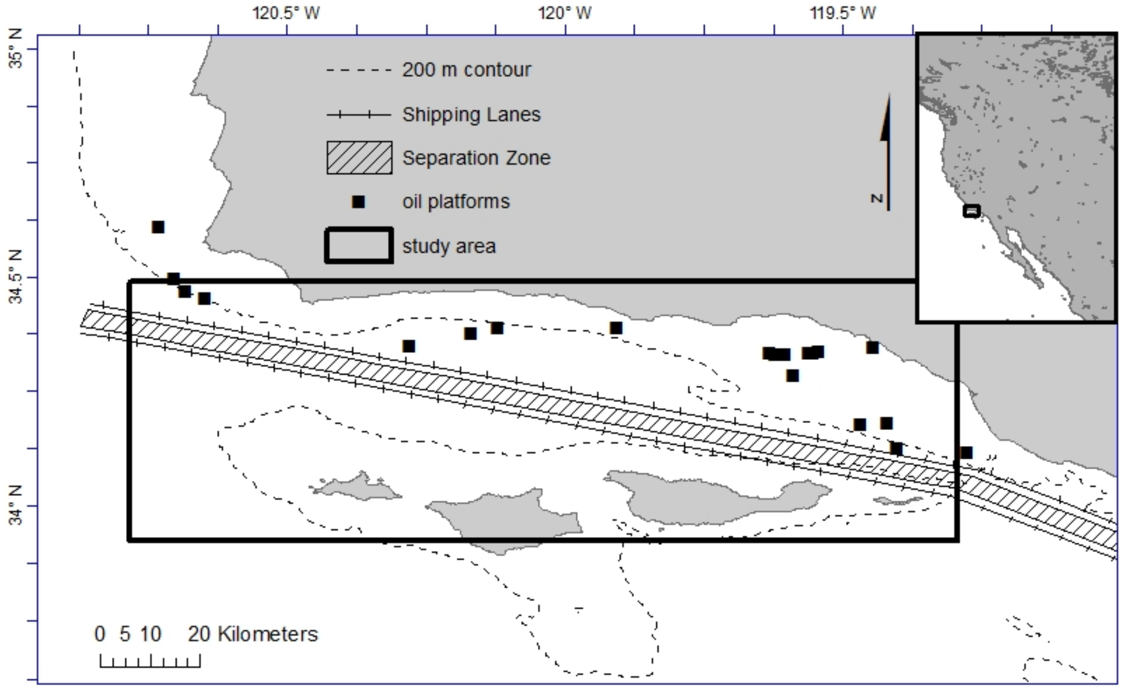

Figure 1.1: The location and extent of the study area, the Santa Barbara Channel. Inset reveals location of study area relative to the North American coast.

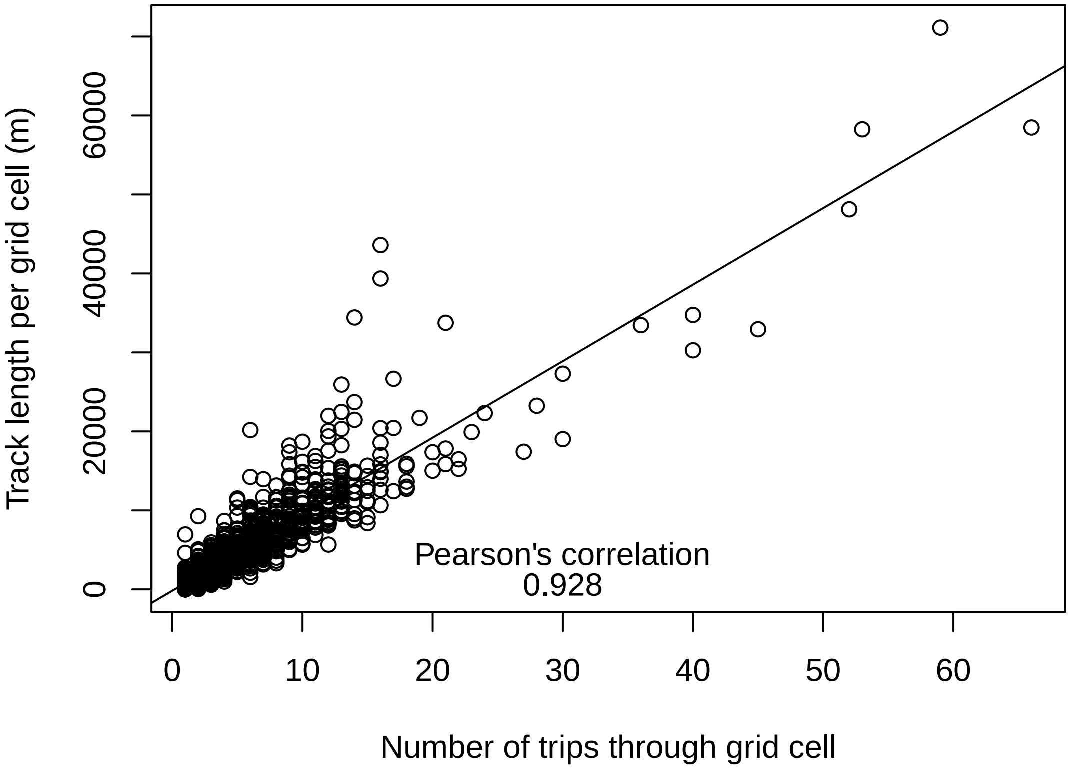

Figure 1.2: Distance of track-line (m) and number of trips through each grid cell, as measures of effort, are highly correlated (0.928, 95% $CI : 0.924 - 0.932$, $p < 0.005$) and indicate distance of track-line is an acceptable measure of effort.

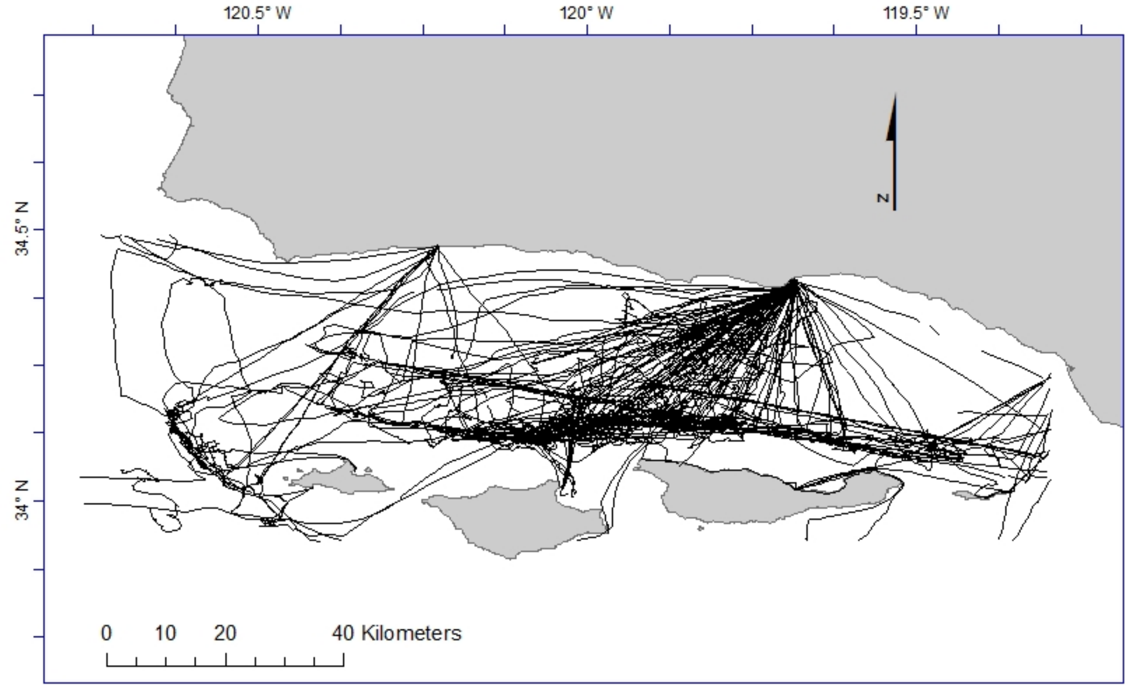

Figure 1.3: Global positioning system (GPS) tracks of research vessels recorded during the 80 trips (November 2001 - September 2009) included in the analysis. Periods where GPS hits were greater than five minutes apart were removed from the analysis and straight line paths were interpolated between the remaining points.

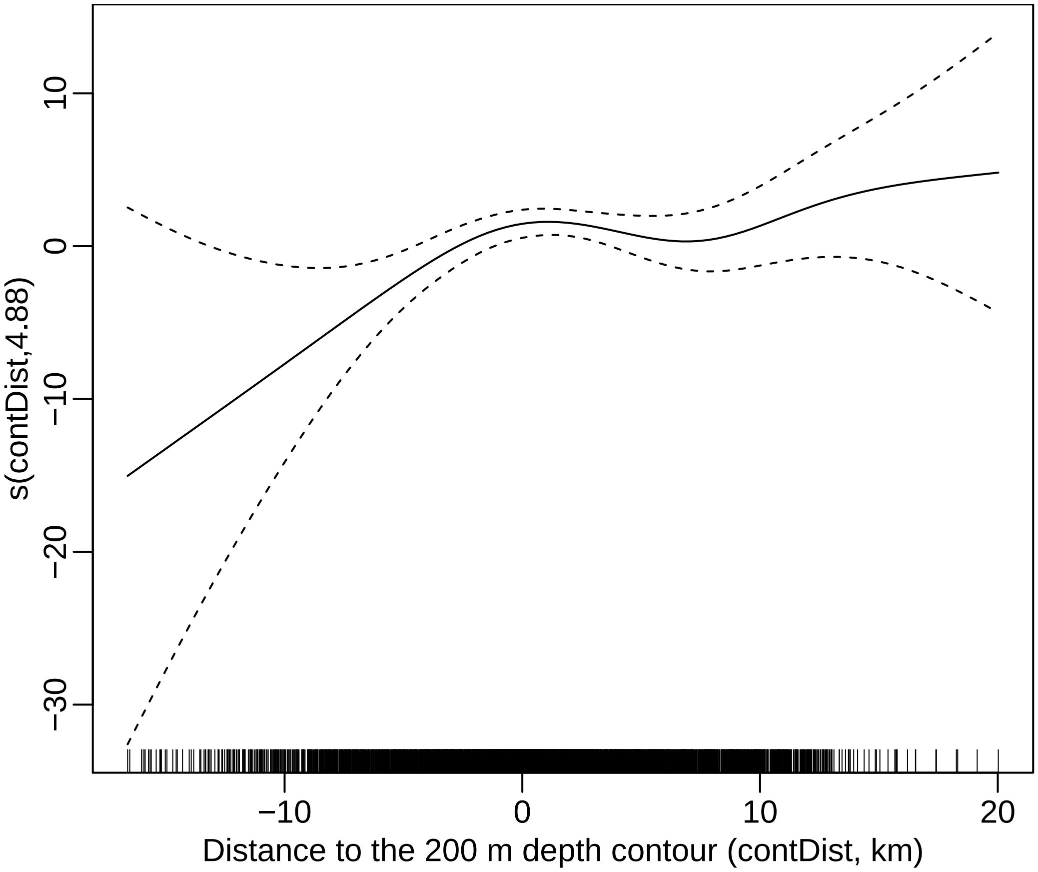

Figure 1.4: Smooth plot of distance to the 200 m depth contour (contDist) on the scale of the linear predictor for the generalized additive model (GAM) of blue whale sighting rates. Estimated smooth functions (solid lines) with 95% confidence intervals (dashed lines) are shown, with the degrees of freedom for nonlinear fits are in parenthesis. Rug plots indicate the distribution of grid cells sampled (with and without blue whale sightings).

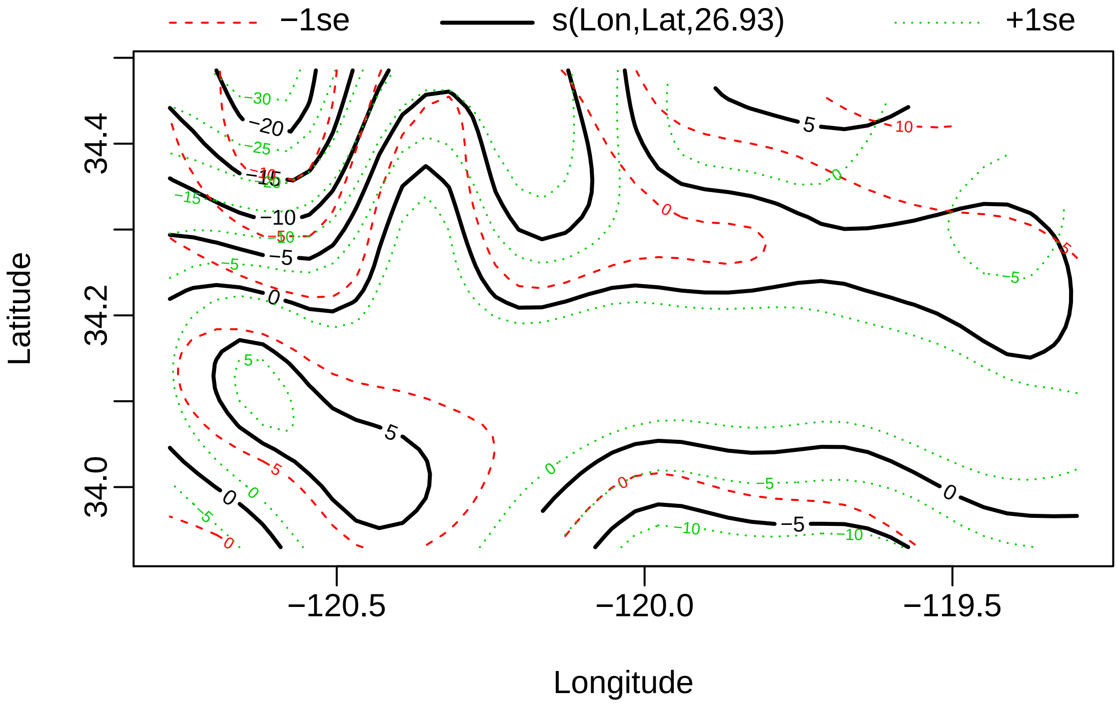

Figure 1.5: Contour plot of the latitude longitude smooth on the scale of the linear predictor for the generalized additive model (GAM) of blue whale sighting rates. The lowest sighting rates are in the northwest corner of the study area. Red and green lines indicate lower and upper 95% confidence intervals respectively. Contour lines are not generated for the northeast corner because of insufficient data.

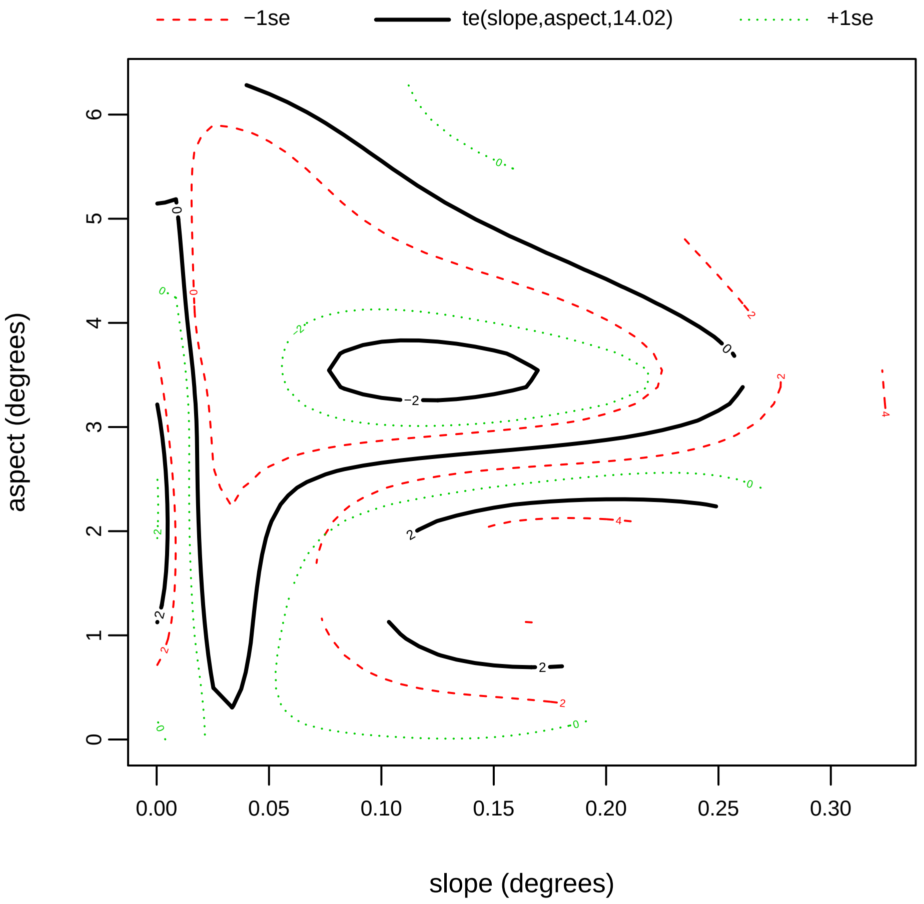

Figure 1.6: Contour plot of the slope versus aspect smooth on the scale of the linear predictor for the generalized additive model (GAM) of blue whale sighting rates. The highest sighting rates are on steep south facing slopes. Red and green lines indicate lower and upper 95% confidence intervals respectively. Contour lines are not generated for steep north facing slopes, where data was insufficient.

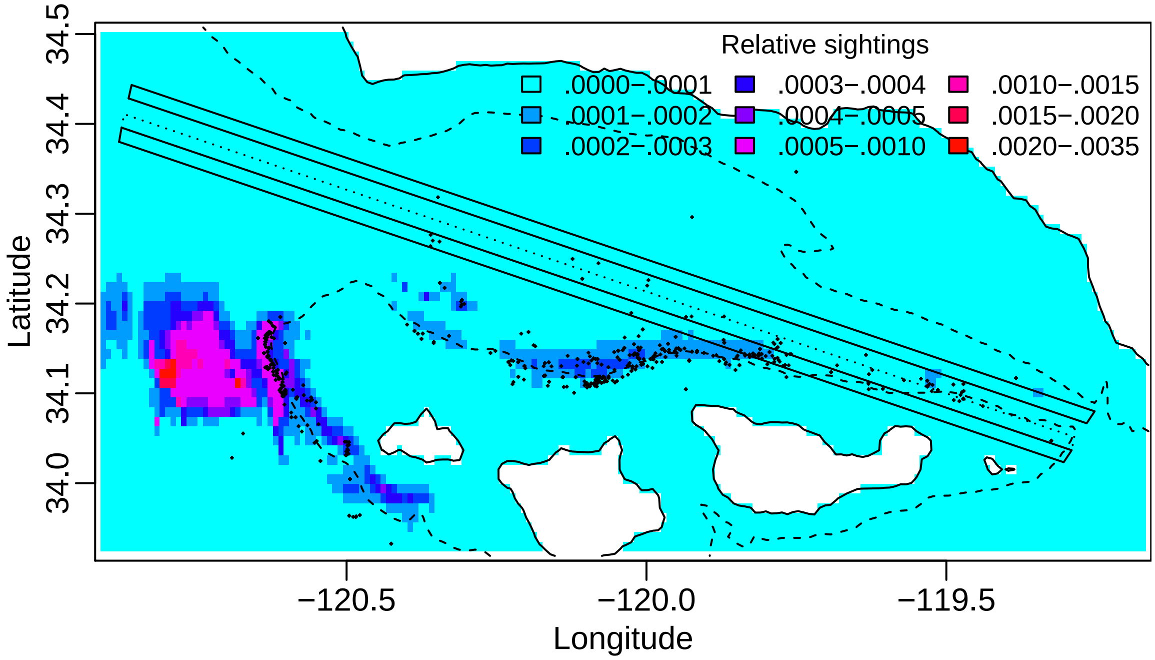

Figure 1.7: Predicted blue whale sighting rates for the Santa Barbara Channel. Black dots reveal independent blue whale sighting locations. The current traffic separation scheme is denoted by the solid lines, while the proposed shift to the southbound lane is indicated by the dotted line. Predictions from final model compare favorably with the overall distribution patterns observed during the surveys.

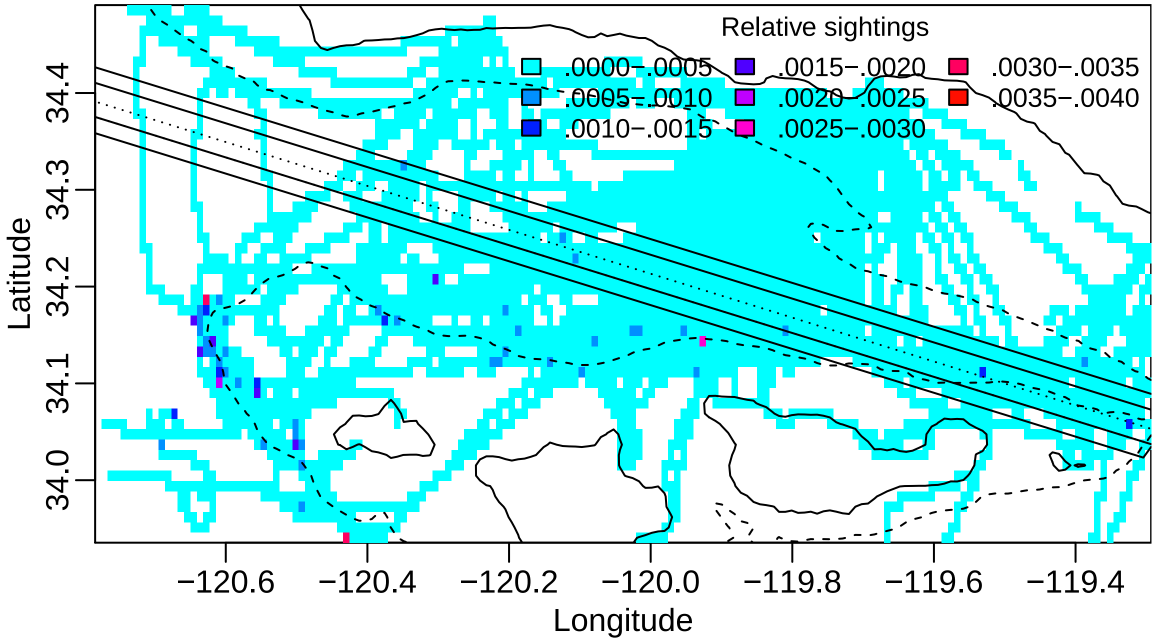

Figure 1.8: Blue whale sightings, corrected by the length of track line, for the Santa Barbara Channel. The dashed line indicates the location of the 200 m depth contour, of which sightings are strongly associated with. The current traffic separation scheme is denoted by the solid lines, while the proposed shift to the southbound lane is indicated by the dotted line. Predictions from final model compare favorably with the overall distribution patterns observed during the surveys.

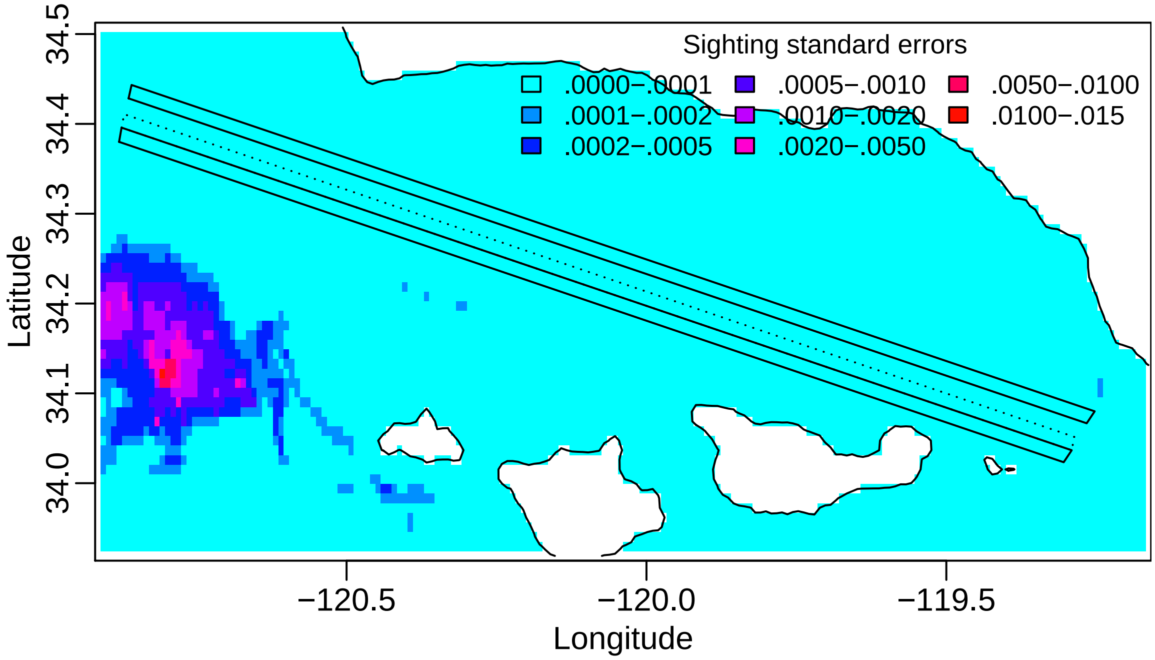

Figure 1.9: Predicted blue whale sighting rate standard errors for the Santa Barbara Channel. Standard errors are highest to the west of San Miguel Island where available data was scarce. Standard errors are consistent throughout the range of the traffic separation scheme. The current traffic separation scheme is denoted by the solid lines, while the proposed shift to the southbound lane is indicated by the dashed line.

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Appendix A

Diagnostic Plots

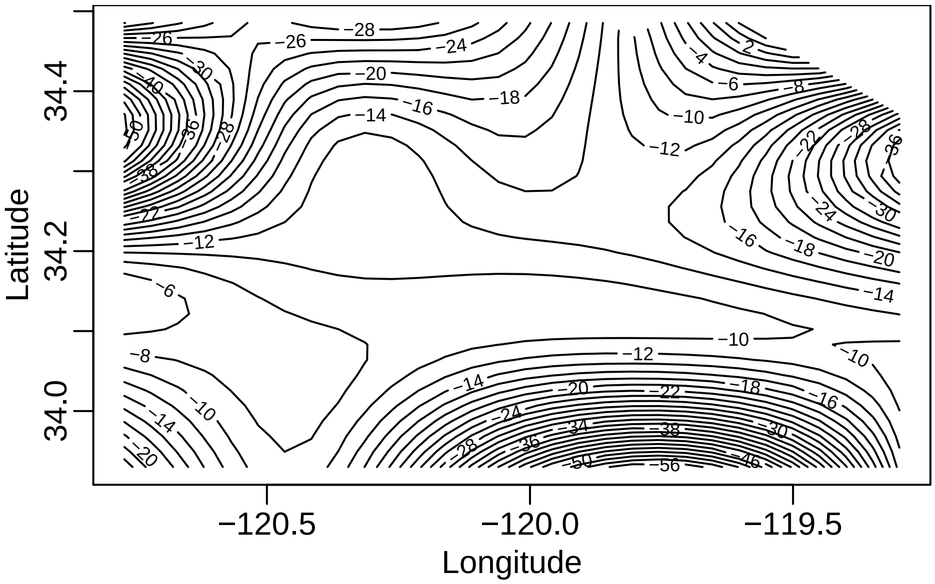

Figure A.1: Contour plot of latitude longitude using an isotropic smooth on the scale of the linear predictor. Based on delta AIC values there is some uncertainty whether to use a tensor product smooth or an isotropic smooth for the spatial covariates. Patterns are similar to patterns using a tensor product smooth (Figure 1.5) and with a delta AIC of less than two, there is a lack of evidence for a difference between the models therefore only the ‘best’ model will be explored. Blank spaces on the figure indicate grid nodes that are too far from available covariates and are left blank to minimize extrapolation.

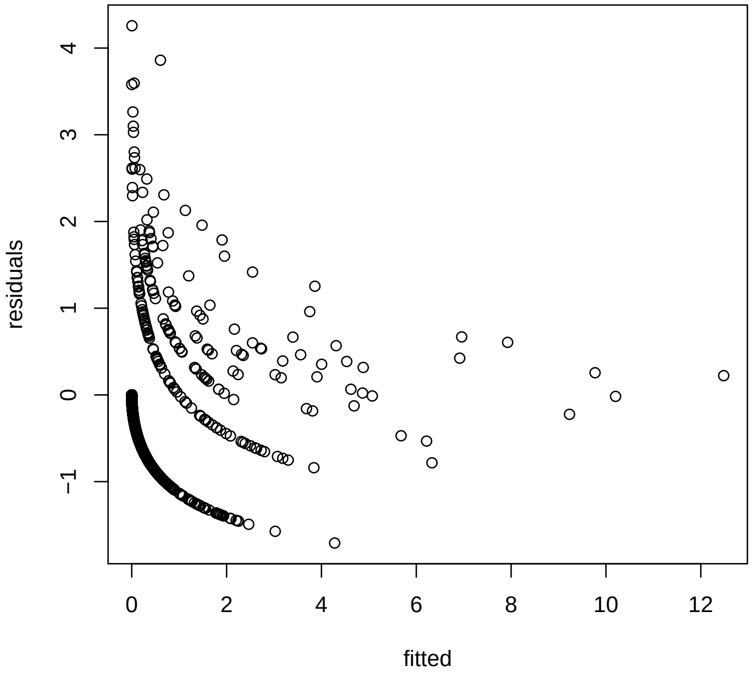

Figure A.2: Residuals versus fitted for the final model.

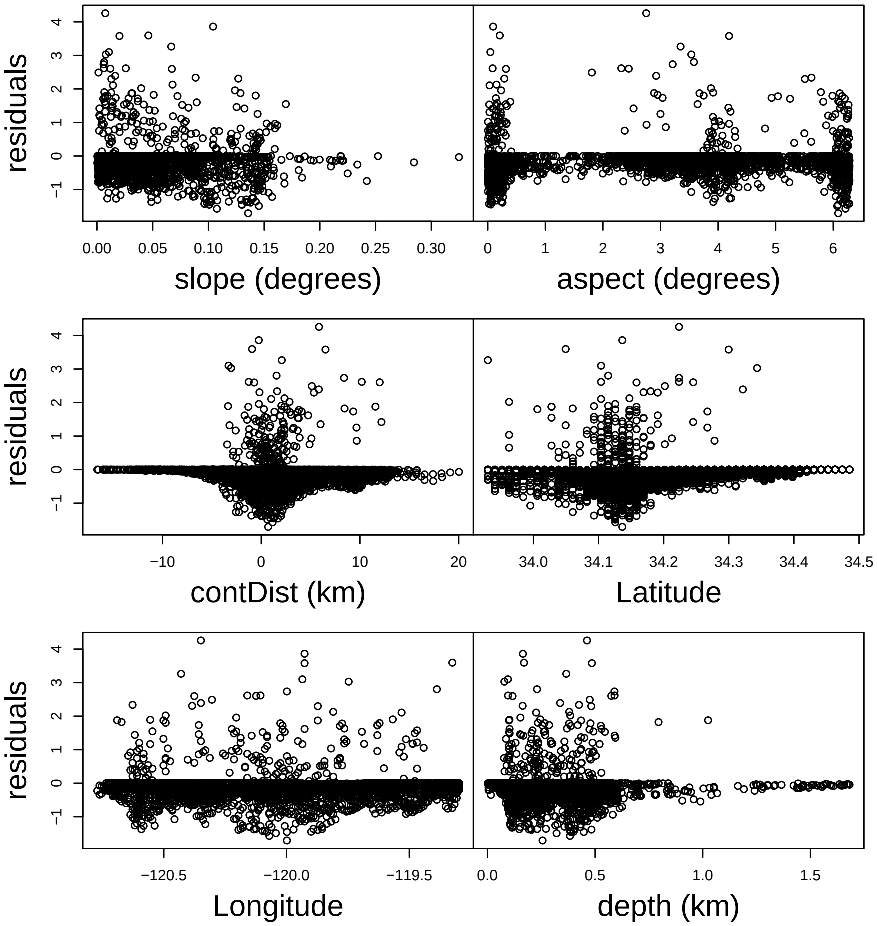

Figure A.3: Residuals versus covariates and possible covariates.

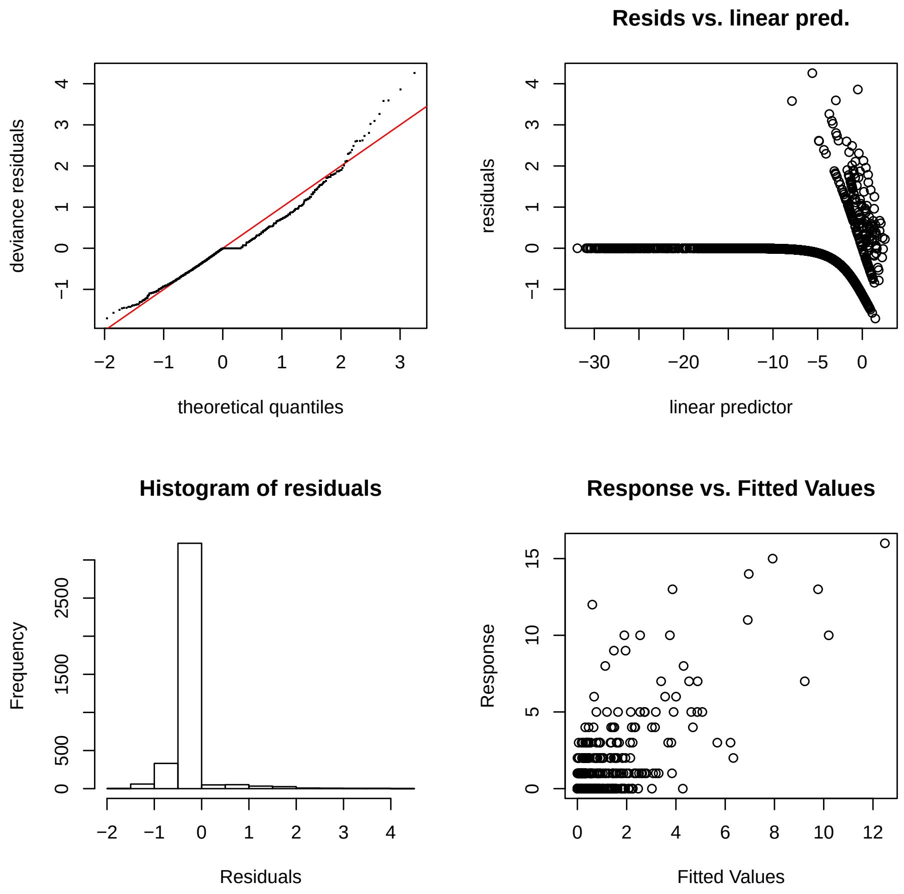

Figure A.4: Results from *gam.check*, in the ‘mgcv’ package, examining the distribution of model residuals.

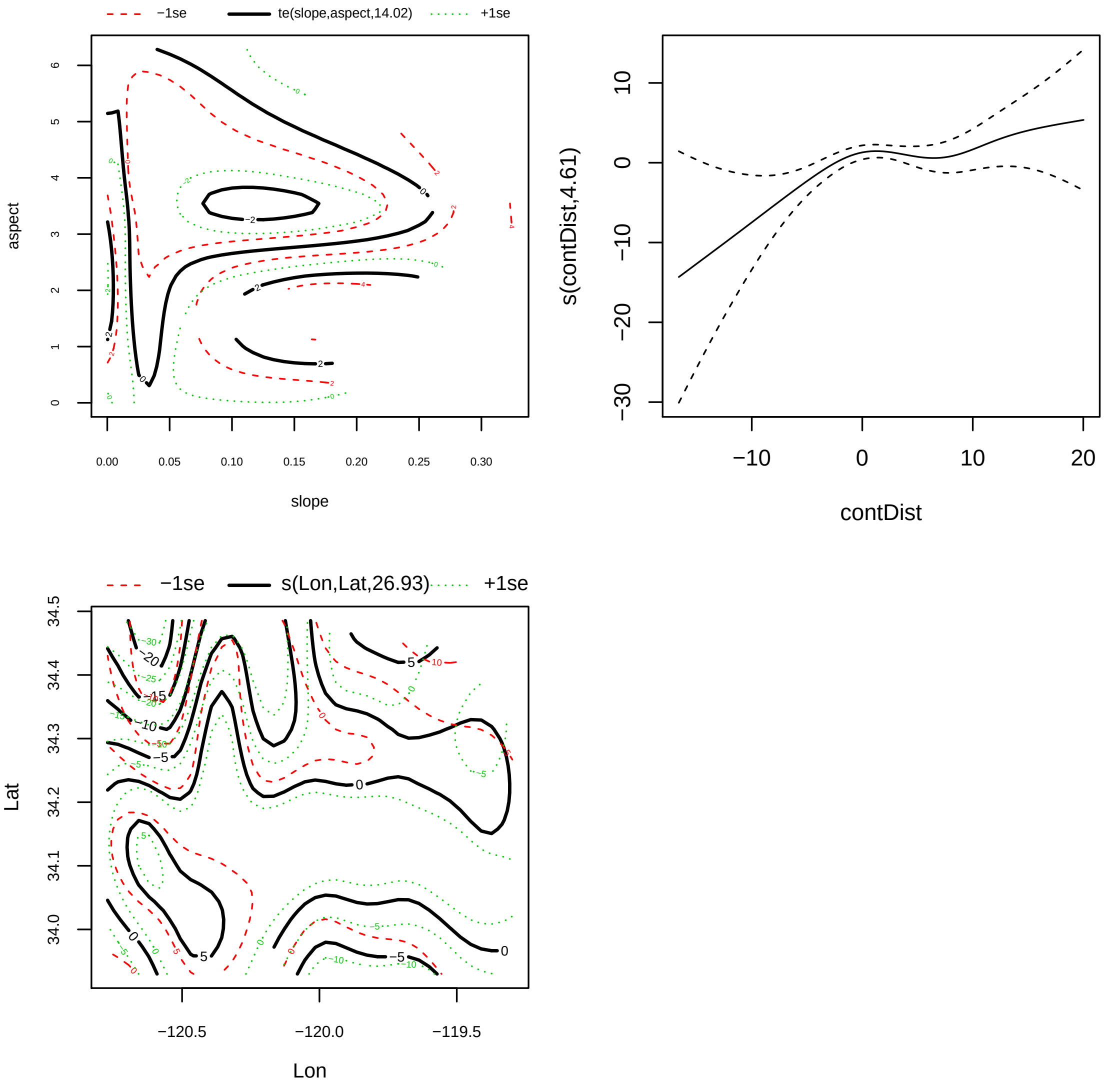

Figure A.5: Non-linear relationships when 15 sightings during the months of October and November are removed from the analysis. Late season sightings may bias model results as male blue whales are known to spend more time at depth reducing their availability to be photographed. Relationships between covariates and sightings did not change when the sightings were removed, therefore the final model included all months.